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Literature Survey of Environmental Concerns Associated with In situ Coal/Oil Shale Operations

Radian Corp., Austin, TX

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LITERATURE SURVEY OF ENVIRONMENTAL CONCERNS ASSOCIATED WITH IN SITU COAL/OIL SHALE OPERATIONS

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16. ABSTRACT The report summarizes available data on in situ coal gasification and in situ oil shale retorting to assess their potential environmental impacts on four areas: (1) groundwater due to leaching of residual materials left underground, (2) those due to subsidence, (3) air quality due to percolation of gases up through the overburden, with subsequent release to atmosphere, and (4) those due to co-produced solid waste consisting of particulate matter coated with condensed hydrocarbons. Impacts on groundwater are the greatest environmental concern; subsidence is of somewhat less, but still significant, concern.

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ABSTRACT

In situ coal gasification and in situ oil shale retorting exhibit a number of unique areas of environmental concern. Available data are summarized to assess the potential impacts to four areas. The areas are impacts on groundwater due to leaching of residual materials left underground, impacts due to subsidence, impacts on air quality due to percolation of gases upward through the overburden with subsequent release to atmosphere, and impacts due to co-produced solid wastes consisting of particulate matter coated with condensed hydrocarbons. Impacts on groundwater are the greatest environmental concern with subsidence being of somewhat less but still significant concern.

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METRIC-ENGLISH UNIT CONVERSION FACTORS*

1.0 m (meter)	=	3.281 feet
1.0 kg (kilogram)	=	2.205 pounds
1.0 kg (kilogram)	=	0.001102 tons
1.0 metric ton	=	1.102 tons
1.0 m^3 (cubic meters)	=	6.289 barrels
1.0 m^3 (cubic meters)	=	264.2 gallons
1.0 l (liters)	=	0.006291 barrels
1.0 l (liters)	=	0.2642 gallons
^oC (degrees centigrade)	=	$\frac{^oF-32}{1.8}$
K (degrees Kelvin)	=	$\frac{^oF-32}{1.8} + 273$
1.0 Nm^3 (normal cubic meter at 273 K)	=	37.32 scf (standard cubic feet at 60°F)
1.0 kcal/kg (kilocalorie per kilogram)	=	1.800 Btu/pound (British thermal unit per pound)
1.0 gr/Nm^3 (grain per normal cubic meter at 273 K)	=	0.02680 gr/scf (grain per standard cubic foot at 60°F)

*For English units used in this report.

SECTION 1

SUMMARY

Publicly available information on environmental areas of concern unique to underground coal gasification and in situ oil shale retorting were gathered. The four areas of concern are:

Impacts on groundwater,

Subsidence,

Post-operational gas leakage to atmosphere, and

Co-produced solid wastes.

Evaluation of the existing data from the Hanna and Hoe Creek sites resulted in the following conclusions for underground coal gasification technology:

The impacts on groundwater are the major environmental concern associated with this technology. Data gathered from small scale field tests in Wyoming show that leaching of material in the gasification area as groundwater reinvades the cavity results in a 2-to-3-fold increase in Total Dissolved Solids. Major components of this increase are Na, $SO_4^=$, and HCO_3^- with lesser increases in Ca, K, Cl^-, and F^-. Significant increases in trace constituents such as NH_3, $S^=$, CN^-, Fe, and B have also been documented. Increases in other trace metals are not apparent from the data. TOC and phenols show large increases as well. Transport of phenols for distances up to 500 feet from the gasified area have been observed at the Hoe Creek site. Current Wyoming regulations require restoration of affected groundwater. Based on Wyoming groundwater quality standards, the contaminated groundwater

in and around the gasified areas at both the Hanna and Hoe Creek sites is still suitable for the same beneficial use as existed before operation. However, if restoration is defined as returning the groundwater to its pre-test composition, extensive treatment will be necessary to remove the constituents which increased as a result of process operations.

Subsidence of the surface has only been observed after the completion of Hoe Creek III. This resulted due to the properties of the overburden and is not considered representative of commercial operations. The potential for surface subsidence at some time after completion of commercial operations is considered high. This assessment is simply based on the fact that no matter how well a commercial site is characterized, the geology is not homogeneous over such large areas as those required for commercial operations. However, the actual occurrence may be decades after completion of operations. Given the remoteness of most western locations where such commercial operations might be conducted, surface displacement may well be an acceptable consequence of necessary energy recovery requirements. The potential for subsidence during and within a few years after termination of operations is considered low because conservative site selection criteria with regard to seam thickness/depth ratios and overburden properties should minimize the probability. Subsidence may also increase the potential for groundwater contamination.

The potential for gas leakage after termination of operations is considered low. This area of concern is directly related to subsidence potential. No such occurrence other than after Hoe Creek III which resulted in surface subsidence has been observed. So long as conservative site selection criteria are applied, surface subsidence within a few years after termination of operations should not occur. This will nearly eliminate the potential for gas leakage.

Particulate matter co-produced with the raw product gas is coated with condensed organic material. The particulate matter is a coal/char/ash

mixture with high carbon content. Handling and disposal may be regulated by the Resource Conservation and Recovery Act. Commercial plants could produce up to 2,000 tons/year of such material depending upon plant size.

For in situ oil shale retorting, the following conclusions resulted from evaluation of the available data:

The potential impacts are very similar to those for underground coal gasification. Impacts on groundwater are the major environmental area of concern for this technology. Extremely limited amounts of field data are currently available. Almost all of the data examined are derived from leaching studies of spent shale produced in laboratory retorts. The leachate compositions are strongly influenced by the retorting method and operating parameters. Shale resources from different locations also show significant differences in leachability studies. Thus, comparison of data is difficult. In general, the leachates show large increases in Na, K, Ca, Si, $SO_4^=$, HCO_3^-, $CO_3^=$, and OH^-. Lower increases are observed for Al, B, Cl, Cr, F, Fe, Li,Mo, Mg, $NO_3^=$, Pb, Sr, and Zn. Large quantities of TOC and phenols also are leached from the laboratory spent shales. Trace metals such as As and Hg exhibit no significant increase in the leachates. An estimate of the impacts on groundwater for the C-a and C-b tracts in Colorado by one of the investigators indicated significant changes in the groundwater quality but that the water might still be suitable for irrigation. As with underground coal gasification, the definition of restoration will be extremely important in determining how extensive any treatment must be.

Subsidence and post-operational gas leakage potentials are considered to be low for this technology since only a relatively small percentage of the oil shale is removed and because the shale swells during retorting. Modified in situ operations have a somewhat greater potential due to mining to remove 20 to 40 percent of the resource prior to explosively rubblizing the column of oil shale. Any effects of the rubblization which are not confined to the intended area could weaken the remaining overburden.

Particulate matter production and handling requirements will be essentially the same as for underground coal gasification. A 2,000 barrel/day commercial facility such as proposed by Geokinetics, Inc., would produce 300 tons/year of such material while a 69,000 barrel/day modified in situ facility could produce up to 24,000 tons/year.

Substantial deficiencies are apparent in the data base for both technologies. Pre-operational baseline groundwater quality data were not gathered at either of the underground coal gasification sites. Field data for groundwater at in situ oil shale retorting sites are sparse. In the latter case, the qualifier must be added that sites where testing has occurred to date were dry or nearly so making monitoring either impossible or extremely long-term. Where possible, any future operations should include sufficient pre-operational groundwater monitoring such that more meaningful impact data can be determined than is the case currently.

Documentation of quality assurance/quality control procedures utilized to ensure analytical data validity and a detailed historical description of groundwater sampling/preservation/analyses procedures also would enhance the ability to assess the data. Availability of raw data would also be helpful.

In the area of subsidence, the major deficiency is the lack of a predictive model. This is true for all mining activities. Major efforts have been underway to overcome this but the complexity of the problem does not bode well for near-term success. Until such a model is available, assessment of the potential for occurrence of subsidence will remain more qualitative than quantitative.

SECTION 2

INTRODUCTION

2.1 BACKGROUND

Development of in situ technologies for the recovery of coal and oil shale has been underway in the United States since the early 1970s and later 1960s, respectively. Because in situ processing is designed to eliminate or, in the case of modified in situ oil shale retorting, greatly reduce the mining operations normally associated with conventional fossil fuels recovery operations, a number of unique environmental concerns are associated with these in situ processes. All are directly related to the in situ processing of the respective resources. The surface processing operations for the in situ-produced gases and liquids are the same as for above-ground coal gasification and oil shale retorting processes with the same types of impacts already known for these types of operations. Areas of environmental concern are the following:

Impacts on groundwater - In situ processing results in the formation of pyrolysis products and ash materials being left underground. As groundwater flows into these areas, leaching of these materials occurs and contamination of the groundwater results. Depending upon the degree of contamination, treatment of this groundwater may be required to prevent transport of contaminants away from the area.

Subsidence - In situ processing involves the removal of large quantities of material. The void volume created may be of sufficient size to cause subsequent failure of the overburden material above the area where processing is conducted leading to deformation of the ground surface with both vertical and

horizontal components of displacement. Subsidence may also result in increased potential for groundwater contamination.

Post-operational gas leakage - At termination of in situ operations, the void volume created underground is filled with gases at pressure. Depending upon the geologic conditions and subsidence potential, there may be a potential for these gases to percolate through the overburden material to the surface with subsequent leakage to the atmosphere.

Co-produced solid wastes - The raw gases produced to the surface during in situ processing contain varying amounts of particulate matter. This particulate matter is removed from the gases and is coated with condensed organic materials which are also contained in the raw product gases. Disposal of this material may require special handling depending upon its properties.

Given these areas of concern, this task was commissioned with the objective of collecting and evaluating existing information on these environmental areas of concern associated with underground coal gasification and in situ oil shale retorting. Completion of this task consisted of the following elements:

Gathering available information on the two processes,

Evaluating the information and, where data were not available, estimating the potential for environmental problems, and

Preparing a topical report on potential environmental areas of concern for the two technologies.

SECTION 3

IN SITU COAL GASIFICATION

In situ or underground coal gasification (UCG) technology offers the potential to recover clean energy from a huge currently unminable coal resource. Given this resource base and the potential for interruption of imported energy supplies, a field-oriented research and development program was initiated by the U.S. Bureau of Mines in 1972 to determine the technical, environmental, and economic feasibility of this technology. The field test activities since that time by government as well as private organizations are briefly described in the following section followed by a section describing the areas of environmental concern associated with UCG, the existing data base, and an assessment of the potential magnitude of the impacts.

3.1 PAST FIELD TEST ACTIVITIES

From the initiation of the U.S. research program in 1972 until the present, a total of 16 major field tests have been completed at seven separate sites--four in Wyoming and one each in Texas, West Virginia and Washington. Of the 17, 14 have received all or nearly all of their funding from the U.S. Department of Energy and its predecessor agencies, the U.S. Bureau of Mines and Energy Research and Development Administration, and three have been conducted by corporations. A total of approximately 35,000 tons of coal were gasified during these tests.

Because of either the limited public data available from or the limited project size and duration of a number of these field tests, the sources of data utilized for preparation of this report consist primarily of that gathered at the two major sites of DOE-sponsored tests in Wyoming, i.e., Hanna and Hoe Creek.

3.2 ENVIRONMENTAL CONCERNS

Four areas of concern unique to UCG are identified as subjects for evaluation in this report. These are, respectively, impacts on groundwater due to post-operational cavity leaching as groundwater reinvades the gasified area followed by down-gradient migration of contaminants; surface subsidence resulting after termination of gasification, post-operational leakage of gases remaining in the cavity to atmosphere by diffusion through overburden materials due to subsidence; and, solid waste disposal considerations for entrained particulate matter removed during primary surface gas cleanup operations. Each of these areas is discussed in the sections which follow.

3.2.1 Impacts on Groundwater

As the UCG process proceeds, a cavity is created within the coal seam where coal has been gasified. During gasification operations, the pressure within this cavity is generally maintained at approximately the hydrostatic pressure within the coal seam to provide partial control of groundwater influx. This partial control in conjunction with the consumption of water in the gasification reaction and the vaporization of water to steam keep the cavity area partially or completely dewatered. The extent of the dewatering is dependent upon the productive capacity of the coal seam aquifer and any adjacent aquifers which become interconnected to the gasified area due to subsurface subsidence immediately above the gasified area. Based on experience gained during the numerous UCG field tests completed to date, it is generally accepted that site hydrologic conditions most favorable to efficient UCG operations consist of a low permeability coal seam such as at the Hanna site with no overlying aquifers in near proximity to the coal seam. These conditions ensure that the gasified area is maintained in a dewatered state.

Under this general set of conditions, groundwater flow is down-gradient into the gasified area when gasification operations are terminated. During this post-operational influx period, the water passes from unaffected coal through cavity walls where water-soluble species such as condensed organic vapors may have been deposited during gasification operations. Thus, these organics may be washed back into the cavity.

In addition, a portion of the residual gases in the cavity will be dissolved in the reinvading groundwater. These gases consist primarily of CO_2, CO, CH_4, and H_2 with lesser (< 1000 ppm v/v) concentrations of total reduced sulfur (H_2S, COS, CS_2, mercaptans) and nitrogen (NH_3, HCN) species assuming oxygen was the injected gasification agent. These concentrations are further diluted with N_2 if air was injected rather than O_2. These dissolved gas species may also participate in complex chemical reactions with species carried in the influxing groundwater leading to dissolution of trace metals as organometallic or inorganic complexes or precipitation of certain trace metals as sulfides.

Within the cavity itself is the thermally affected ash residue as well as unaffected coal and pyrolysed coal and any roof material which spalled into the cavity during or after gasification. These materials have been exposed to a wide range of temperatures ranging from ambient up to 2500°F. Exposure to these temperatures—especially at the upper end of the range—results in thermal alteration of the mineral matter. These alterations theoretically make the material more or less susceptible to leaching by the groundwater, depending on the species of interest. As a further complication to the sequence of potential contamination steps, the cavity temperature is cooled as the groundwater reinvades the void. Thus, certain species which are readily leached at elevated temperatures may reprecipitate or may undergo chemical transformation as the cavity cools.

After the pre-operational hydrologic gradient has been reestablished, the contaminated groundwater begins to move out of the cavity and

spread to the surrounding down-gradient groundwater regime. The movement of some of the dissolved species, e.g., dissolved organics, is impeded due to the sorptive capacity of the unaffected coal surrounding the gasified area. Further, depending upon the mineral composition of the ash, some degree of cation-anion sorption or interchange occurs. Biologic activity may also contribute to changes in the groundwater composition over time.

The time frame for reestablishment of pre-test hydrologic characteristics is dependent upon the characteristics of each individual aquifer. At the Hoe Creek site, cavity refill has occurred within a period of a few months to a year. At the Hanna site, cavities of similar size have taken up to five years to refill. This range of time has resulted in significantly different observations at the two respective sites as would be expected.

3.2.1.1 Impacts Observed to Date

Significant groundwater monitoring activities have been conducted at the Hoe Creek and Hanna sites since 1975 and 1977, respectively. Large volumes of data have been gathered from numerous wells at each site. However, a true baseline, i.e., one year, sampling and analysis program was not completed at either site prior to initiating site operations. The pre-test monitoring activities consisted of sampling a number of wells drilled specifically for groundwater monitoring within close proximity to the process wells used for each individual field test. Coverage thus was limited to areas of no more than a few acres. No larger-scale hydrologic characterization or groundwater monitoring were done since this level of effort would have precluded any other work given the budgets devoted to the two sites.

The potential for interference between individual test locations on the site exists but the degree is unknown. Whether the data reflect any interferences is also unknown. The data evaluated for this report were those available in the literature and do not represent the raw data. Therefore, the quality of the data has not been determined with regard to

internal quality assurance/quality control aspects. Sample collection, preservation, and analytical procedures over the several year period during which the data were gathered may have been modified. If so, the effects on the data interpretation are unknown. Therefore, the data presented in this report serve only as relative indications of the impacts observed and demonstrate that certain identified contaminants are produced which migrate to the surrounding groundwater. With these broad limitations with regard to the data in mind, the subsequent discussion documents the observations at the Hoe Creek and Hanna sites, respectively.

Hoe Creek Observations

The Hoe Creek site is located about twenty miles south of Gillette, Wyoming. The coal seams gasified were the Felix No. 1 and No. 2 seams (about 35 feet total thickness separated by 10 to 20 feet) at depths of 150 to 200 feet. As shown during initial hydrologic characterization and data confirmed during gasification operations, the overburden is a poorly consolidated mixture and the strata make up a leaky aquifer system with sustainable pumping rates from the coal of three to four gal/min. The reported baseline water quality in the Felix No. 2 coal seam (1) is given in Table 1. According to current State of Wyoming guidelines, this water is classified as suitable for livestock (Class III). This classification is necessary to estimate the minimum restoration requirement established by Wyoming statute.

The changes observed after completion of gasification at the Hoe Creek I site are shown in Table 2 (1). The largest effects observed are substantial increases in the major cations and anions with the resultant large increase in Total Dissolved Solids. These changes are most likely due to leaching of the ash matrix within the cavity plus leaching of thermally altered overburden material which collapsed into the cavity during and after gasification. Thus, the major impact of the technology is to increase the

TABLE 1. FELIX NO. 2 COAL SEAM BASELINE WATER QUALITY

Component	Concentration Units	Pre-Gasification[a] Value
Alkalinty	mg/l	407±30
Al	µg/l	0-10
As	µg/l	0-1
Ba	µg/l	100±100
HCO_3^-	mg/l	496±40
B	µg/l	86±30
Br	mg/l	0-0.1
Cd	µg/l	0
Ca	mg/l	36±10
$CO_3^=$	mg/l	0
CL^-	mg/l	13±5
CN^-	mg/l	0.00-0.01
Fe	µg/l	0-10
Pb	µg/l	0-1
Li	µg/l	34±5
Mg	mg/l	10±4
NH_4^+ as N	mg/l	0.55±0.05
NO_2 as N	mg/l	0
NO_3 as N	mg/l	0.02±0.01
Phenols	µg/l	1±1
Dissolved Organic Carbon	mg/l	5.8±3
K	mg/l	5.4±0.5
Total Dissolved Solids	mg/l	703±70
Na	mg/l	214±15
$SO_4^=$	mg/l	154±80
$S^=$	mg/l	0.3±0.2
Zn	µg/l	224±200

[a]The "±" values indicate the approximate range of results for seven wells.

TABLE 2. CHANGES OBSERVED IN GROUNDWATER QUALITY AFTER HOE CREEK I FIELD TEST

Species	Concentration Units	Inside Burn Boundary (Injection Well) Post-Gasification 83d	Outside Burn Boundary					
			DW-1 (10 feet)			EM-1 (100 feet)		
			During Gasification	Post-Gasification 3d	Post-Gasification 83d	During Gasification	Post-Gasification 3d	Post-Gasification 83d
Alkalinity	mg/l	63	595	693	430	837	686	636
Al	µg/l	220	0	10	20	0	10	10
As	µg/l	8	1	1	0	0	0	1
Ba	µg/l	0	200	600	0	0	0	1
HCO_3^-	mg/l	0	725	845	524	1020	836	776
B	µg/l	710	90	110	360	90	90	70
Br	mg/l	1.0	0.2	0.3	0.7	0.0	0.1	0.1
Cd	µg/l	0	0	0	0	1	0	1
Ca	mg/l	570	35	110	220	110	100	78
CO_3^{-2}	mg/l	24	0	0	0	0	0	0
Cl^-	mg/l	37	10	10	22	6.6	7.4	9.5
CN^-	mg/l	0.43	7.0	48	0.14	4.0	5.0	0.01
Fe	µg/l	30	380	37000	1700	4400	18000	160
Pb	µg/l	1	2	0	0	2	2	7
Li	µg/l	310	30	50	190	50	50	50
Mg	mg/l	19	8.1	28	55	26	26	18
NH_4^+ as N	mg/l	19	0.49	2.1	20	0.80	0.77	0.84
NO_2 as N	mg/l	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO_3 as N	mg/l	0.01	0.19	0.01	0.07	0.01	0.01	0.02
Phenols	µg/l	41	15	1000	340	83	15	2
K	mg/l	57	4.3	7.5	25	7.7	7.7	6.1
Dissolved Solids	mg/l	3390	699	989	2020	1170	1240	1050
Na	mg/l	320	240	350	310	330	320	310
SO_4^{-2}	mg/l	2200	37	67	1000	250	320	250
S^{-2}	mg/l	4.0	0.7	1.1	—	0.3	2.6	0.6
Zn	µg/l	10	50	20	1200	120	30	20

already high levels of Na, $CO_3^=$, and $SO_4^=$ with lesser absolute increases in Ca, Mg, Cl^-, and F^-.

Changes in trace element concentrations are not as clear cut. Data gathered (1) from the Hoe Creek I site indicate increases in dissolved Fe, B, and Al, again presumably from the coal ash matrix, but no change in Cd, Pb, or As concentrations within the gasification cavity.

Other components of interest are those gaseous species formed as a result of gasification which may be dissolved in the groundwater upon termination of operations. These constituents are $S^=$, NH_3, and phenols. Again, after Hoe Creek I there are significant increases in these constituents within the cavity and at outlying wells with the relative change in phenol concentrations being the most striking.

The observations from the later Hoe Creek II and III tests are in general agreement with those from the Hoe Creek I but several significant differences should be noted. The effects of Hoe Creek I were isolated in the Felix No. 2 coal seam. Hoe Creek II and, to a much greater extent, Hoe Creek III operations were large enough to lead to gasification of both the Felix No. 1 and 2 coal seams with subsequent interconnection of the two coal seam aquifers with the overlying sand aquifer. The background water compositions for the three aquifers (3) are given in Table 3 and a comparison of cavity water compositions for Hoe Creek II and III in Table 4. Although the three-aquifer system was determined to be interconnected during site characterization efforts prior to Hoe Creek I, the Felix No. 2 coal seam is of significantly better quality than the other two aquifers. In comparing the compositions of the cavity waters from Hoe Creek II and III, differences in Na, Ca, $SO_4^=$, and TDS levels stand out. The reasons for the large differences when the two sites are within 1000 feet of each other are unclear. Differences in operating parameters have been proposed to explain the differences with dissimilar temperature histories during gasification leading

TABLE 3. BACKGROUND WATER COMPOSITIONS FOR THREE HOE CREEK AQUIFERS*

	Aquifer		
	Felix No. 2 Coal	Felix No. 1 Coal	Sand
Electrical Conductivity (μmho/cm)	1080 ± 150	2070	2700
pH	7.5 ± 0.1	7.1	7.7
Temperature (°C)	11.0 ± 3	10.5	10.0
Alkalinity	401 ± 33	260	270
Boron	0.10 - 0.05	50	80
Calcium	36 ± 10	190	270
Chloride	13 ± 5	8	9.3
Cyanide	<0.01	<0.01	<0.01
Magnesium	10 ± 4	73	67
Potassium	5.4 ± 0.5	8	16
Sodium	214 ± 15	190	320
Sulfate	154 ± 80	800	1300
Sulfite	0.3 ± 0.2	0.6	0.6
Dissolved Solids	700 ± 70	1600	2000

*Concentrations for ionic species in mg/l.

TABLE 4. CAVITY WATER COMPOSITIONS - HOE CREEK II AND III

	Well A** (Hoe Creek II)				Well B** (Hoe Creek III)		
	106 d*	170 d	271 d	451 d	149 d	201 d	380 d
Temperature (°C)	38	32	37	33	59	67	51
pH	8.6	8.5	8.8	8.8	7.5	8.0	8.6
Conductivity (micro-mho/cm)	1800	1800	1450	1220	4960	4100	4000
Bicarbonate	260	276	260	244	80	76	28
Boron	2.2	2.2	2.3	3.1	4.4	4.3	3.5
Calcium	75	62	42	29	240	310	250
Chloride	26	59	23	27	95	75	59
Cyanide	0.14	0.08	0.03	0.09	0.074	0.23	0.12
Magnesium	25	13	11	6.5	75	75	59
Potassium	85	79	64	46	120	110	110
Sodium	250	240	220	180	720	610	532
Sulfate	760	630	600	280	2200	2200	2000
Total Sulfide	42	6	40	57	1	0.5	0.2
Dissolved Solids	1290	1260	—	782	3400	3340	3050

*d - Days after the corresponding gasification experiment.

**Concentrations of ionic species in mg/l.

to more readily leachable ash in the cavity of Hoe Creek III. The intermixing of waters from the overlying sand aquifer with coal seam waters could also account for a major portion of the differences in terms of TDS, $SO_4^=$, Mg, and Ca. Apparently the mixing was more extensive during and after Hoe Creek III than that experienced during Hoe Creek II and dominated by the overlying sand aquifer. Sharp localized variations in hydrologic characteristics may also be a partial explanation although no data to support this have been reported.

The concentrations of NH_3 and phenols in the Hoe Creek II and III cavities approximately 18 months after termination of gasification (after reestablishment of hydrologic equilibrium) were 26 and 15 ppm NH_3 and 0.09 and 0.01 ppm phenols, respectively. These compare to background levels of 0.5 to 1.0 ppm and 0-to-2 ppb, respectively. Much higher levels of phenols were observed at wells removed from the cavities with the maximum concentration being 38 ppm at the Hoe Creek II site and 10 ppm at the Hoe Creek III site. Similarly, a maximum NH_3 concentration of 50 and 15 ppm was observed at the two sites at wells located about 30 and 70 feet from the cavity boundary, respectively. Due to concern that a plume of phenols might be transported outside the permit area because of elevated phenol levels at wells up to 400 feet from Hoe Creek II, additional monitoring wells were drilled to detect any such transport. Analyses show transport away from the cavity areas of Hoe Creek II and III in all three aquifers for distances ranging up to 500 feet within the Felix No. 2 coal seam (outside the site permit area) and 250 feet in the Felix No. 1 coal seam (4). Concentrations up to about 500 and 200 ppb were determined for the Felix No. 2 and No. 1 coal seam aquifers, respectively.

Hanna Observations

The Hanna site is located about two miles south of Hanna, Wyoming, and about seventy miles northwest of Laramie. The coal seam gasified was the Hanna No. 1 seam which is thirty-feet thick at depths ranging from 165

feet (Hanna III) to 400 feet (Hanna I). In contrast to the Hoe Creek site, the groundwater productivity and geologic setting reflect a low water availability (sustainable pumping rate of 10 gal/hr) from the coal seam, very low water movement rates (10 feet/year), and a well confined aquifer (5,6). The overburden is a well consolidated competent shale. Background water quality data for the Hanna III site are given in Table 5. Due to the limited number of samples taken prior to initiation of operations, a baseline composition is also given for Well CBO-152 for which quarterly analyses data are available from September 1980 through December 1982 (7). This well is located approximately 1300 feet southeast of the Hanna I site which should be a sufficient distance that no effects of testing would be observed given the low water movement rates in the coal seam aquifer. The water is a Class III water suitable for livestock, although there is currently no use of this groundwater due to the low productivity rate. The large difference in $SO_4^=$ concentration most likely reflects sharp localized water quality differences since the Hanna III site is located close to the coal seam outcrop.

Due to the slow water movement rates, the observed impacts are confined to the area of the Hanna III site. Post-gasification water samples were obtained from 11 wells at Hanna III during the periods June 1978, approximately one year after gasification, through November 1978 and from September 1980, with samples collected from three wells at Hanna III, through December 1982 on a quarterly basis. The cavity was still not totally filled at this time—over five years after shutdown.

Elevated concentrations of boron were observed in all of the available cavity monitoring wells. A maximum level of over 5 mg/l was observed. The Hanna III baseline concentration was less than .1 mg/l. The level of boron rose sharply after gasification and then decreased gradually with time to 1 to 2 mg/l by December 1982.

TABLE 5. HANNA NO. 1 COAL SEAM BASELINE WATER QUALITY

Component	Hanna III* Site Average	Well** CB-152
pH	8.6	8.2
Temperature (°C)	10	9.2
Na (mg/1)	510	545
K (mg/1)	-	9.7
Ca (mg/1)	-	5.9
Mg (mg/1)	-	2.9
Fe (mg/1)	-	2.2
HCO_3^- (mg/1)	1106	724
$SO_4^=$ (mg/1)	19	490
Cl^- (mg/1)	-	11.6
F^- (mg/1)	1.86	2.6
NH_3-N (mg/1)	1.15	3.7
$S^=$ (mg/1)	<0.1	<0.1
Total Dissolved Solids	1223	1508
Total Organic Carbon	41	23.5
Phenols (µg/1)	<10	<10
CN^- (µg/1)	-	<50
As (µg/1)	-	<10
Ba (µg/1)	-	<40
B (µg/1)	40	<10
Cd (µg/1)	-	<5
Cr (µg/1)	-	<10
Cu (µg/1)	-	<20
Hg (µg/1)	-	<2
Mn (µg/1)	80	<25
Mo (µg/1)	-	<50
Pb (µg/1)	-	<10
Se (ug/1)	-	<10
V (µg/1)	-	<50

*Average of samples from six to ten wells from which samples were collected.

**Average of ten quarterly samples collected from 9/80 to 12/82.

Sulfide concentrations exhibited a pattern similar to boron, except the initial sharp increase occurred later after gasification. Concentrations over 10 mg/l were common with most values reported over 4 mg/l followed by a sharp decline to about 0.1 mg/l in early 1982.

Ammonia concentrations increased sharply immediately after gasification from less than 5 mg/l to over 25 mg/l. Concentrations then decreased gradually to apparent baseline conditions.

The detection of phenols in cavity waters appeared much later than for other pyrolysis products reflecting the slow fill rates for the cavities at the Hanna site with a maximum concentration of 40 µg/l. Samples from the Hanna I and Hanna II, phases II and III cavities showed levels above .1 mg/l.

The concentration of total dissolved solids in the postburn cavity groundwaters increased from approximately 1200 mg/l to an average of 3000 mg/l. After gasification, concentrations continued to increase slowly, remaining well above baseline at the end of 1982.

Sulfate concentrations increased gradually from a level of less than 50 mg/l to 1000 mg/l. The dissolution of gypsum is the most probable source of sulfate in the leachate.

Bicarbonate concentrations at Hanna III increased slightly from a baseline level of 1100 mg/l to approximately 1700 mg/l after gasification, and then decreased rapidly to about 700 mg/l.

After gasification, sodium concentrations increased gradually from approximately 500 mg/l to an average of 900 mg/l. Cavity groundwaters exhibited increased fluoride concentrations after gasification, initially increasing to 7 mg/l followed by a gradual decrease to near baseline.

The concentration of total organic carbon in the cavity groundwaters decreased from a level of approximately 45 mg/l to an average of 20 mg/l. All cavity wells showed a flat response in concentration over time. No explanation for this apparent anomaly has been proposed. No analyses for CN^- were conducted at the Hanna site.

Two sets of samples were collected from ten wells to determine the concentrations of EPA organic priority pollutants. The results are shown in Table 6 (8) for the four wells in which concentrations were above detection limits.

These observations highlight the long-term nature of monitoring activities required to establish impacts under such hydrologic conditions as those at the Hanna site since all testing ceased in 1980 and Hanna III was completed in August 1977. They also indicate the difficulty in determining restoration requirements. The interpretation of the data is extremely difficult other than very general trends which generally agree with the Hoe Creek results although the magnitudes of changes are in some cases much lower, e.g., phenols.

3.2.1.2 Assessment of Impact Potential

The impacts observed to date are a 2-to-3-fold increase in TDS levels due to UCG operations plus significant increases in the concentration of phenols, NH_3, $S^=$, CN^-, B, and possibly trace metals. The need to restore the groundwater for any further operations has been established by statute in Wyoming. However, the specific needs and treatment steps to achieve restoration are necessarily vague. Under hydrologic conditions such as those at Hanna impacts could well be confined to a very localized area with extensive time lag after termination of operations before water is available for treatment. The large increases in salt loading as well as the other changes observed will be dispersed as groundwater flow is reestablished although for low flow regimes the time frame may be decades. The data

TABLE 6. EPA ORGANIC POLLUTANT LEVELS IN WATER SAMPLES AT THE HANNA SITE[a]

	Well Number[b]							
	H-I-3		H-III-4		H-III-7		H-IV-2	
	10/82	09/83	10/82	09/83	10/82	09/83	10/82	09/83
Acenaphthene	2						9	9
Naphthalene	89	8					5	9
Phenanthrene	2						2	4
Toluene	14	6	5	9				1
Benzene	10	4				1	32	38
Dimethylphenol	120	70						6
Phenol	230	310	8	15				6
Bis(2-ethyl-hexyl)-phthalate				11				

[a]All concentrations in ppb.

[b]H-I-3 = Hanna I experiment, Well No. 3, which is completed into the gasified area.

H-III-4 = Hanna III experiment, Well No. 4, which is completed into an overlying aquifer directly above the gasified area.

H-III-7 = Hanna III experiment, Well No. 7, which is completed into the Hanna No. 1 coal seam approximately five feet from the cavity boundary.

H-IV-2 = Hanna IV experiment, Well No. 2, which is completed into the gasified area.

gathered to date are more useful in setting site characteristics suitable for UCG operations than for deriving specific numerical values of impact levels. Experts in the technology agree that UCG operations should not be conducted at sites where groundwater quality and quantity is such that current or projected use would be jeopardized. If restoration to pre-operational quality is required, application of UCG technology may be precluded as a future energy source due to the excessive costs. Current technology limits restoration approaches to pumping and treatment at the surface using conventional wastewater treatment steps. Without the development of unique in situ treatment schemes, no other approach appears feasible.

The impacts on groundwater resources are the primary environmental concern associated with UCG technology. The monitoring results indicate that significant degradation can occur. Using stringent site selection criteria designed to protect groundwater resources potentially can both greatly reduce and delay the impacts but future treatment may be required.

The data available to fully assess these impacts are extremely limited. A program to provide the data needed to fully assess these impacts would include a UCG field test program at a site chosen based on criteria established as a result of the recent experiences. The program elements to derive the data include pre-test baseline data gathering for groundwater quality, site hydrology, coal and overburden compositions, test operation with concurrent monitoring, and long-term post-operational monitoring. These elements would establish the levels of impacts as a function of time. Laboratory and modeling programs would be important supporting elements to simulate in situ conditions such that a predictive groundwater flow model could be developed. Definition of regulatory groundwater restoration requirements would be necessary such that treatment schemes could be designed and tested at bench- and pilot-scale levels to achieve specific removal efficiencies set by the restoration requirements.

Under any circumstances, this potential impact remains the major environmental concern associated with UCG. Existing data indicate that significant impacts are inherent to the technology. Given the current status of UCG technology, the primary mitigation approach may be the adoption of conservative site selection characteristics with regard to hydrology and groundwater quality such that impacts are confined to the smallest possible area to allow time for development of improved restoration technology.

3.2.2 Subsidence

As with any mining technology, the potential for subsidence is an area of concern for UCG. This potential is dependent upon the depth of the mining activity, the size of the cavity created, the ratio of depth to mined thickness, the lithology and physical properties of the overburden, and the effects of thermal alteration on the immediate overburden. The timing as well as the degree of such subsidence is dependent upon these factors.

3.2.2.1 Impacts Observed to Date

In all of the UCG field tests conducted to date, subsidence to the surface has not been observed with one exception. Within thirty days after termination of the Hoe Creek III test, surface subsidence occurred. The overburden material was unconsolidated and no stable arch was formed over the cavity after gasification. The overburden material settled resulting in surface expression in the same shape as the shape of the cavity (plan view) with a maximum of three feet of settling observed to date (9).

By contrast, at the Hanna site post-test coring (10,11,12,13) of the test sites showed the same basic pattern independent of cavity size. The subsurface subsidence extended approximately thirty feet (one seam thickness) above the gasified area but no further. Cavity sizes up to 80 feet x 80 feet x 30 feet at a depth of 250 feet and 40 feet x 70 feet x 30

feet at a depth of 165 feet were created at Hanna. The overburden material directly overlying the coal is a well consolidated competent shale provides support such that a stable arch is created within a short distance above the cavity—about thirty feet at this site.

Similar results were observed at the Rawlins, Wyoming, site when Gulf R and D Corporation conducted the largest UCG test in the U.S. (14). The seam is about 25-feet thick, dipping from horizontal at an angle of about 63 degrees. Test operations were conducted at a vertical depth of about 600 feet and 8,500 tons of coal were gasified.

3.2.2.2 Assessment of Impact Potential

Observations to date indicate that subsidence can be reduced through use of site selection criteria outlining seam thickness/depth ratios and overburden characteristics. However, commercial operations will affect much larger areas than the small field tests conducted to date with cavity dimensions of several hundred feet. Subsidence to the surface is highly probable with the major question being timing. If subsidence can be delayed until well after termination of UCG operations, this impact may be acceptable so long as no surface facilities are affected when it occurs. However, no model currently exists which provices for estimates for either the amount of subsidence or its timing. This is the case for all mining technologies, not just in situ gasification. Only semi-quantitative empirical relationships have been developed for longwall coal mining operations. A considerable effort has been made and continues to develop a predictive model as well as to monitor in situ stresses and subsidence features during the operation of the field test. These field data serve as a preliminary limited base. In order to provide the necessary inputs to any model, the following types of data are required:

Lithology of the overburden,

Physical (strength) properties of each individual overburden stratum,

Effects of elevated temperatures on stratum directly overlying the coal,

Bulking factors for the near overburden,

In situ stress changes within each stratum as a function of time, and

Cavity dimensions as a function of time.

Given the complex nature of the problem and the difficulty of gathering the last two data elements in the list above, the potential for development of an accurate predictive model is not likely in the near future. Therefore, conservative design parameters based on low seam thickness/depth ratios and resource recovery efficiencies of about 50 percent (the same as for current room and pillar mining) will most likely be utilized to minimize surface subsidence.

Subsurface subsidence is of greater concern because it can lead to interconnection of aquifers, thereby increasing the total degree of groundwater contamination associated with the technology. A certain amount of subsurface subsidence directly over the gasified area is inevitable. With proper site selection regarding overburden characteristics and aquifer locations relative to the coal seam, the amount can be controlled and greatly minimized. Given the current state of the art, again conservative site selection characteristics will most likely prevail. This may limit the first commercial operations to sites where either no aquifers overlie the coal or any overlying aquifers are at least several seam thicknesses above

the coal and there is currently no beneficial use of groundwater from these aquifers.

3.2.3 Post-Operational Gas Leakage

When UCG operations are terminated, a hot gas-filled cavity remains. The gases left slowly cool as groundwater invades the gasified area. The potential for the gas to diffuse through the overburden material eventually leaking to atmosphere is an area of concern due to the presence of such gases as CO, CH_4, H_2, and reduced sulfur species. Such an occurrence is linked most directly to the potential for subsidence at a given UCG site.

3.2.3.1 Observations to Date

As for the occurrence of subsidence, the only incident of post-operational gas leakage occurred after the completion of the Hoe Creek III experiment when subsidence to the surface occurred. The amount and composition of the gases which entered the atmosphere are unknown. The visual evidence of leakage (steam release) was of short duration (several days) with presumably lesser flow over some longer unknown amount of time. Based on post-operational gas compositions monitored from other field tests, the dry gas composition is approximately as follows:

H_2	40 - 50% (v/v)
CO	3 - 6%
CH_4	1 - 2%
CO_2	40 - 50%

Small amounts (ppm levels to 0.05% v/v) of H_2S, ethane, propane, COS, ammonia, and light hydrocarbons also are present. The total volume available from the gasified area at Hoe Creek III is estimated at 100,000 scf based on the cavity volume and low temperature and pressure conditions in the cavity. For commercial operations, the volume may be on the order of 50 to 100 MM scf.

3.2.3.2 Assessment of Impact Potential

The potential for such occurrences is directly tied to the potential for subsidence to the surface after termination of UCG operations. With proper site selection to minimize subsidence, i.e., low seam thickness/depth ratios and presence of competent overburden strata, this should not be an area of serious concern.

3.2.4 Co-Produced Solid Wastes

The UCG product gas contains particulate matter which is entrained in the gas stream. At sufficiently high gas velocities within the production well casing, large particles of material can be lifted to the surface. These materials are removed from the product gas stream during primary gas cleanup operations with the largest materials dropping out during gas transport from the well field to the central gas processing plant and the fine particles being removed during quench operations. The particulates are coated with condensed organics. These organics are pyrolysis products from the coal. The particulate matter is coal, char, or partially pyrolyzed coal. Due to the presence of these organic coal pyrolysis products coating the particulates, these materials may be considered a hazardous waste requiring special handling and disposal within the limits established by the Resource Conservation and Recovery Act.

3.2.4.1 Observations to Date

Particulate loading and size distribution data and elemental compositions of the materials have been reported for three UCG locations (15,16,17). Monitoring was conducted during the Hanna II and IV tests with loadings ranging from 0.002 to 0.36 gr/scf and 0.001 to 0.043 gr/scf, respectively. The particle size range sampled was less than 20μ with greater than 80 percent of the particulates being less than 5μ. The elemental composition showed a high carbon content material similar to coal/char mixes.

During Rawlins II a loading range of .006 to 1.07 gr/scf was determined with a significant portion of the materials being from 20-to-1,000μ in diameter. The MAF combustion value of the particulate matter was about 15,000 Btu/lb—the same as the coal.

Measurements from the partial seam test near Centralia, WA, gave a loading range of 0.4-to-30 gr/scf with averages of 5.5 and 1.16 gr/scf for the two production wells sampled. The size distribution range covered was less than 13μ with 80-to-95 percent being less than 5μ. From 10 to 40 percent of the as-collected material by weight was removed during an extraction with CH_2Cl_2. The removed material was condensed oils/tars on the particulate matter. The elemental composition of the material showed it to be a mixture of coal, char, and ash.

The total particulate loadings determined during these three tests give only an indication of the particulate loadings that might be expected during commercial operations. Gas flow velocities at the production wells were generally much higher than proper design specifications would dictate. As a result, erosional problems in piping systems have been experienced during most of the UCG field test series. For commercial operations, a design particulate loading of 0.1 gr/scf has been assumed (18,19).

3.2.4.2 Assessment of Impact Potential

The degree of any problem associated with the disposal of particulate matter removed from the product gas is in direct proportion to plant size. For a 25 MW power plant with loadings of 0.1 gr/scf, daily production of 500-to-700 pounds of material (about 100 tons/year) is estimated, depending upon the amount of condensed oils on the particulates. This material may well be temporarily stored on site with transportation by licensed, certified carriers to an off-site hazardous waste storage site rather than constructing an on-site disposal area. Another option may be on-site incineration. The small amount of material most likely would not be conducive to

any beneficial use in terms of waste heat recovery should incineration be conducted. In this case, the magnitude of the problem is relatively minor.

For a UCG facility designed to supply sufficient product gas for production of 250 MM scfd of SNG, the amount of material produced using the same loading value of 0.1 gr/scf is 500-to-700 pounds/hour or 6-to-8 tons/day (about 2000 tons/year). Disposal of this amount of material would most likely require an on-site disposal site built to handle hazardous wastes. Given the complexity of such an SNG facility, such a disposal site is most likely already included in the plant design.

SECTION 4

IN SITU OIL SHALE RETORTING

In situ oil shale retorting is a similar process to in situ coal gasification. Primary differences are production of a refinable liquid product with the retort gases being a by-product and the oil shale is an extremely high ash fuel for the process. The areas of environmental concern are basically the same as for UCG technology. The following sections briefly describe selected field activities and discuss the potential for impacts on groundwater resources, subsidence, post-operational gas leakage, and co-produced solid wastes.

4.1 PAST FIELD ACTIVITIES

In situ oil shale processing encompasses two approaches to recovering shale oil. These are known as true in situ and modified in situ (MIS) retorting. The difference between the two is that modified in situ retorting includes partial mining prior to rubblization of the oil shale bed in preparation for operations. Modified in situ retorting was developed as a solution to the major processing problem associated with the resource, i.e., oil shale has essentially no permeability to allow for fluid flow between wells. Forming a rubblized column of oil shale by partial mining followed by explosive fracturing creates sufficient void volume throughout the column to allow for low pressure operation and suitable resource recovery efficiencies.

Field tests of true in situ retorting were conducted by the Laramie Energy Technology Center (LETC) from 1968 to 1977 at a site near Rock Springs, WY. Geokinetics, Inc., has successfully field tested a true in situ process designed specifically for shallow (< 100 feet) oil shale resources at a site south of Vernal, UT.

Modified in situ retorting has been developed by Garrett Research and Development Company and by Occidental Oil Shale, Inc., at Logan Wash, CO, where from 20-to-40 percent of the shale is removed by mining. The remaining shale is explosively rubblized into the mined void creating a bed of fractured shale for retorting from top to bottom.

4.2 ENVIRONMENTAL CONCERNS

The areas of concern unique to in situ oil shale retorting are the same as those for UCG. The potential for impacts on groundwater due to leaching of organic materials from the spent shale are an additional area of concern for this technology since the retorting yields a refinable liquid product. Each of the four areas of concern identified for UCG is addressed in the following sections.

4.2.1 Impacts on Groundwater

After the completion of in situ oil shale retorting operations, a bed of spent shale plus mobilized but unrecovered shale oil remains in the spent retort. As groundwater percolates through the spent shale bed it leaches the material picking up inorganic and organic contaminants which are then transported through the groundwater regime.

4.2.1.1 Impacts Observed to Date

Limited data are available from field monitoring activities. Generally, the field sites were dry or with such low permeabilities that field monitoring was not suitable for obtaining data in a suitable time frame. Assessment of leaching potential has, therefore, been conducted using simulated retorting operations in the laboratory with subsequent leaching of this

material to determine impacts which might occur. Wide variations in experimental techniques, analytical methods, and spent shale sources have occurred. Comparison of data from different researchers is, therefore, extremely difficult and no attempt is made to draw conclusions from different studies. Major variations in leachate composition are observed due to the different oil shale samples used in the studies as well as retorting conditions.

The leaching of organics from simulated in situ spent shale (20,21,22) indicates that in thirty days, from 1.0-to-38 milligrams of total organic carbon (TOC) may be leached for every 100 grams of in situ spent shale at water temperatures of 20°C to 80°C. Most of this organic carbon is solubilized after the passage of the first few pore volumes of water through leaching columns. Limited data are available on the organic characterization of leachates indicating that about equal quantities of acidic, basic, and neutral materials are present in leachates, and that organic nitrogen and phenols are present at concentrations greater than 0.1 ppm.

Similar results have been reported (22,23) for, respectively, a simulated in situ spent shale from a steam-combustion run of LETC's 10-ton retort and a Paraho spent shale.

The mass of TOC leached from spent shales, produced in the simulated in situ retorts at the Lawrence Livermore Laboratory (LLL), ranges from 1.5 to 6.9 milligrams per 100 grams of spent shale for inert gas runs, from 1.0 to 4.4 milligrams per 100 grams of spent shale for combustion runs, and from 2.9 to 11.8 milligrams per 100 grams of spent shale for a combustion run using recycle gas. Overall, for all of the retorting conditions investigated, the range was 1.0 to 11.8 milligrams of TOC per 100 grams of spent shale.

In contrast, the data obtained using spent shales from the simulated in situ retorts at the Laramie Energy Technology Center (LETC) range from 10.0 to 38 milligrams of TOC per 100 grams of shale for a combustion run and

a steam-combustion run. The difference between the LLL and LETC spent shales is probably related to differences in the simulated in situ retorts and in the retort operating conditions.

This summary indicates that the lowest amount of organic material was leached from combustion spent shales and that significantly higher amounts of organic material were leached from inert and combustion-recycle spent shales. The high levels of organic material removed from combustion-recycle spent shale is due to the adsorption of organics from the recycle gas onto the spent shale as the gas is supplied behind the reaction front.

Considerably higher amounts of organic material were leached during the continuous-flow column experiments than during the batch experiments. Elevated water temperatures had little effect on the amount of organic material leached from spent shale produced during ordinary combustion runs, enhanced the leaching of organic material from spent shale produced during inert gas runs, and inhibited the leaching of organic material from spent shale produced during combustion runs using recycle gas when distilled water was used.

TOC provides only an estimate of the total amount of organic material present in leachate but provides no indication of the types of organic compounds present. Table 7 presents a summary of data which describes general categories of organic constituents—acidic, basic, and neutral fractions—present in leachate. The acid fraction may contain such organic compounds as carboxylic acids, and phenols; the basic fraction may contain organic compounds like amines; and the neutral fraction may contain hydrocarbons. These data indicate that retorting conditions influence the types of organic compounds that are present in leachate. The neutral fraction is the most predominant fraction associated with leachate derived from spent shale produced during inert gas runs.

TABLE 7. QUANTITIES OF ORGANIC FRACTIONS LEACHED FROM SPENT SHALE AFTER THIRTY DAYS

Water	Experiment[a]	Organic Fraction	Leached Organic Fractions, µg/100g: Inert Gas Retorting[b]	Combustion Retorting	Combustion and Recycle Gas Retorting
Distilled	Batch 20°C	Acid	370, 880	680	360
		Base	510, 540	460	290
		Neutral	880, 1050	860	280
		Total	1760, 2470	2000	930
	Batch 80°C	Acid	450, 720	500	330
		Base	330, 360	610	470
		Neutral	350, 890	180	520
		Total	1130, 1970	1290	1320
Synthetic Groundwater[c]	Batch 20°C	Acid	920	420	—
		Base	440	370	—
		Neutral	1600	660	—
		Total	2960	1450	—
	Batch 80°C	Acid	1100	500	—
		Base	590	330	—
		Neutral	2300	360	—
		Total	3990	1190	—

[a]All experiments conducted with particle size range of 0.06–0.3 inches.

[b]The two values correspond to two separate inert-run spent shales.

[c]Synthetic groundwater had a conductivity of 12,000 µmho/cm and a pH of 9.

Source: (20)

The concentrations of organic nitrogen and phenol are summarized in Table 8. This table indicates that organic nitrogen and phenol concentrations are significantly higher in leachates produced from inert-run spent shales than from combustion-run spent shales. This is consistent with the TOC data discussed previously. The lowest level of these constituents occurs in leachates from combustion runs. Lower water temperatures appear to enhance the solubilization of both organic nitrogen and phenols. A comparison of Tables 7 and 8 indicates that about 20 percent of the base fraction is organic nitrogen.

Studies of leaching inorganics from spent shale (20,24,25,26,27,28,29) have been conducted on simulated spent shales as well as on field cores and measurements of waters which have reinvaded a spent shale retort. These studies indicate that the principal ions in the leachate are $SO_4^=$, Na, HCO_3^-, and OH^-. Other constituents, such as Cl^-, F^-, Li, Mo, Pb, and Zn occur at lower levels. The leachates typically have a high electrical conductivity and a high pH. Most of these constituents are solubilized after the passage of the first few pore volumes of water. This type of behavior is identical to that described previously for organics.

The quantity of various inorganics leached from in situ spent shale is difficult to assess on a general basis. This is due primarily to the extreme variability of inorganics in oil shales, the wide range in groundwater quality encountered in areas of oil shale deposits, and the fact that most available data on leaching were obtained using distilled water (24,26,30,31).

Available data indicate that there are major differences between the chemical composition of leachates obtained with groundwater and distilled water (26,31). This is primarily because, with distilled water, ions are being removed from the spent shale by desorption or chemical reactions. When groundwater is used, the chemical components in it may enter into reactions with components in the spent shale or in the leachate itself. Available

TABLE 8. QUANTITIES OF ORGANIC NITROGEN AND PHENOLS LEACHED FROM SPENT SHALE

Water[a]	Experiment[a]	Constituent	Mass Leached Per Unit Mass, µg/100g		
			Inert Gas Retorting	Combustion Retorting	Combustion and Recycle Gas Retorting
Distilled	Batch, 20°C	Organic Nitrogen	70-100	70	90
		Phenols	41-43	25	22
	Batch, 80°C	Organic Nitrogen	70-140	40	130
		Phenols	30-35	23	15
Synthetic Groundwater	Batch, 20°C	Organic Nitrogen	90	90	70
	Batch, 80°C	Organic nitrogen	90-100	70	60

[a]All experiments conducted with particle size range of 0.14 cm - 0.64 cm.

Source: (20)

leaching data obtained using actual groundwater used a water with high total dissolved solids (TDS) and alkalinity. However, in some areas, good quality groundwater with low TDS and alkalinity is found. In these cases, leaching experiments using distilled water may be more representative than those using poorer quality groundwaters. Nevertheless, distilled-water data should be used with caution when evaluating the leaching of inorganics from in situ spent shales. The results of the two groups of studies are presented separately.

Four studies have reported leaching data that were obtained for groundwaters (24,25,27,28). These investigators used a composite groundwater from Rock Springs, Wyoming, where lean deep deposits of oil shale suitable for true in situ development are located, and two groundwaters from Utah.

Table 9 summarizes data obtained from LETC's Rock Springs Site 6 true in situ field experiment (24). The data presented in columns (1) and (5) of Table 9 provide an approximation of the composition of the groundwater before combustion was started. These data are for observation wells, located 90 feet to 200 feet from the burn area.

Column (2) of Table 9 gives the average quality of water obtained from a series of wells at which underground combustion (pattern wells) was started and from which products were recovered. The water samples were taken during the burn. These values represent leachate composition during passage of the first few pore volumes of water. A comparison of column (2) with columns (1) and (5) provides an estimate of the effect of in situ retorting at Site 6 on local groundwater quality. This comparison shows that all reported parameters, with the exception of pH, increase (typically fourfold or more), pH decreases slightly.

Column (3) in Table 9 gives data for a series of wells drilled in the retorted area four years after the burn. These values represent leachate

TABLE 9. WATER QUALITY ANALYSIS OF WELLS NEAR LETC's SITE 6, TRUE IN SITU FIELD EXPERIMENT

Constituent	Concentration, mg/liter: Observation Wells 6 Months After Combustion Analysis Date: 11/71 - 8/72 (1)	Pattern Wells During Combustion Analysis Date: 12/70 - 7/71 (2)	Pattern Wells 4 Hr After Combustion Analysis Date: 8/75 (3)	Observation Well Q 4 Yr After Combustion Analysis Date: 8/75 (4)	Observation Well Q 6 Mo After Combustion Analysis Date: 11/71 - 8/72 (5)
B	11	-	40	78	5.5
Ca	11	58	2.7	3.7	8.1
Cl	931	4250	592	2700	241
F	9.1	53	25	50	4.2
K	6.9	34	101	30	4.8
Mg	4.7	230	6.1	5.0	4.9
Na	1830	8900	3460	8400	723
NO_3	1.2	4.5	-	-	1.1
Si	-	-	16	12	-
CO_3	671	1940	1032	5300	465
HCO_3	1300	9750	3046	6000	361
SO_4	254	4810	2400	25	119
TDS[a]	5029	30,030	10,721	22,604	1938
pH	9.7	8.6	9.3	9.6	9.6

[a]Computed as sums of ions shown.

Source: (24)

composition at the burn site four years after the burn. With two exceptions—K and pH, which increase—the values in column (3) are less, by a factor of 2 or more, than those in column (2). Most parameters decrease by a factor of 2 to 3 except Ca, Mg, and Cl^-, which decrease by factors of 7 or greater. An estimate of the effect of the burn on the original groundwater quality in the retorted area after a long period of time is obtained by comparing columns (1) and (3). This comparison shows that, while most parameters are high relative to original levels, Ca, Cl^-, and pH decrease.

Elevated concentrations of many constituents persist in the burn area for years after completion of retorting. The major components of the leachate (which occur at greater than 1000 mg/1) are Na, Cl^-, $SO_4^=$, HCO_3^-, and $CO_3^=$, Ca, Mg, K, and F^- occur at moderate levels. Some constituents decrease as the leachate is transported through the groundwater aquifer. These constituents are Ca, Mg, Cl^-, and $SO_4^=$.

Table 10 is a summary of laboratory-scale batch leaching studies (25) in which Rock Springs groundwater and Colorado oil shale were used. Column (1) presents the composition of the groundwater used for the leaching experiments. The water is similar in composition to that of Table 9. Columns (2) and (3) summarize the composition of the leachate after 450 hours of contact. These data show that retorting conditions significantly affect the levels of ions in the leachate. For the low-temperature inert run, Ca decreased significantly, Mg and Na decreased slightly, Zn, $CO_3^=$, and Fe remained about the same, and Cu, K, Li, and pH increased. In contrast, for the high-temperature run, $CO_3^=$, Fe, and Mg decreased significantly, Na decreased slightly, Ca, F^-, and Zn remained the same, and B, Cu, K, Li, and pH increased.

Parker (27,28) used two separate Utah groundwaters and Utah oil shale to investigate the effect of temperature on leachate quality. Four hundred and fifty grams of crushed Utah shale were retorted in a laboratory retort at temperatures ranging from 430 to 1000°C. Small samples (67 and 86 g)

TABLE 10. MATERIAL EXTRACTED FROM SPENT SHALE AFTER 450 HOURS OF LEACHING WITH ROCK SPRINGS GROUNDWATER

Constituent	Leachate Composition (mg/l)[a] Original Groundwater mg/l (1)	High Temperature Inert Gas (2)	Low Temperature Inert Gas (3)
B	8.5	41.2	-
Ca	6.25	6.25	0.21
Cu	trace	0.26	0.15
CO_3	3,300	1,053	3,050
F	26.5	26.5	-
Fe	0.77	0.38	0.70
K	38.5	75.8	45.5
Li	0.19	4.17	0.28
Mg	11.75	1.8	9.0
Na	5,065	4,538	4,450
Zn	0.19	0.20	0.19
pH	9.3	12.6	9.55
Sum of Constituents	8,458	5,748	7,556

[a]Cylindrical cores of Anvil Points oil shale, 3.65 cm in diameter and 5.0 cm long, were retorted and leached in 200 ml groundwater in a continuously stirred, batch-leaching cell. Over increasingly long periods, 20 ml samples were taken for analysis and replaced by equal volumes of groundwater.

Source: (25)

were leached at 35°C and 90°C with 200 ml of Douglas Creek or Birds Nest Creek groundwater for 21 days. The data indicate that conductivity, pH, and alkalinity are significantly reduced in leachates derived from spent shales retorted at 1000°C relative to those retorted at 780°C. However, even though the levels of these constituents are reduced, they are still high enough (e.g., pH = 11) to cause significant degradation of the local groundwaters. The higher temperature (1000°C) has little effect on selenium, arsenic, or fluorine,and tends to enhance the leachability of boron. High pH (approximately 11), conductivity (7,000-15,000 μmho/cm), and alkalinity are reported for 1000°C.

Several investigations have been concerned with the leaching of inorganics by distilled water (20,24,26,29). The results of these investigations may be used as approximations of what may occur if in situ spent shale is leached by groundwater with a TDS of less than 1000 mg/l and an alkalinity of less than 50 mg/l as $CaCO_3$. Data are summarized in Table 11 for TDS leached in the first three studies.

Quantities of specific inorganic constituents leached from simulated in situ spent shales with distilled water are summarized in Table 12. There are significant differences between the data of the various investigators. The differences may reflect variations in analytical methods, retorting conditions, or oil shale composition.

The data of Parker et al (26) indicate that temperature and retorting atmosphere have the following effects on leachate composition:

> The concentrations of Ca, Fe, K, Na, and Sr are higher in leachates from combustion runs than from inert-gas runs.
>
> The levels of Li, Sr, and Cr in leachates derived from high-temperature combustion and inert runs are much higher than from low-temperature runs.

TABLE 11. SUMMARY OF QUANTITIES OF TDS LEACHED FROM SIMULATED IN SITU SPENT SHALE BY DISTILLED WATER

Source	Experiment	Water	Quantity of Leached TDS, mg/100g		
			Inert Gas Retorting	Combustion Retorting	Combustion with Recycle Retorting
Simulated in situ spent shale					
UCB (20)	30-day batch, 20°C	Distilled	110-160[a]	510[b]	1000[b]
UCB (20)	30-day batch, 80°C	Distilled	230-360[a]	470[b]	850[b]
UCB (20)	30-day batch, 20°C	Synthetic Groundwater	0,140[a]	420[b]	600[b]
UCB (20)	30-day batch, 80°C	Synthetic Groundwater	0, 70[a]	250[b]	520[b]
UCB (20)	Continuous flow	Distilled	230-440[a,d]	2000,2700[d]	2100,2800[d]
Texas Tech. (26)	15-hour batch	Distilled	80->1120	405-944	
LETC (24)	5-minute batch, 25°C	Distilled	-	250-760	

[a]Determined for two unique samples of inert-run shale.

[b]Single value for one each combustion and combustion-recycle spent shales.

[c]Synthetic groundwater had a conductivity of 12,000 μmho/cm and a pH of 9.

[d]TDS leached after 80 hours in, respectively, a 12-inch-long and a 6-inch-long column. Two unique samples were tested in each column for the inert run and one sample was used for the combustion and combustion-recycle run.

TABLE 12. LEACHATE COMPOSITION OF SIMULATED IN SITU SPENT SHALE

Reference	[20]			[23]	[25]				[29]		
	LLL 100-Ka Retort				Laboratory-Scale Retort				Laboratory-Scale Retort[d]	Field Retort 5E	
	Low Temperature Inert	High Temperature Combustion	High Temperature Combustion-Recycle	LETC 10 ton High Temperature Combustion	Low Temperature Inert	High Temperature Inert	Low Temperature Combustion	High Temperature Combustion	High Temperature Steam	High Temperature Steam	
Experiment type[a]	B,C	B,C	B,C	B	B	B	B	B	B	B	
Particle size range, inches.	0.08-0.3	0.08-0.3	0.08-0.3	1-12	2x1.5 cores	2x1.5 cores	2x1.5 cores	2x1.5 cores	-	-	
Contact time, batch.	30 days	30 days	30 days	5 min	15 hour	15 hour	15 hour	15 hour	-	Soxhlet Extraction	
Pour values for continuous-flow columns.	31	31	31	-	-	-	-	-	-	-	
Constituent	Constituent Concentration, mg/100 g										Data Summary, Simulated In Situ Retorts
Al	-	-	-	-	0.39-1.4	1.6-2.8	0.065-1.4	-			0.065-2.8
B	-	-	-	0.075-0.14	-	-	-	-	0.01-0.03	0.001-0.010	0.001-0.14
Ca	-	-	-	3.67-67	9.1-14	44-99	97-160	99-210	0.4-2.5	0.03-2.21	0.03-210
Cl	-	-	-	5.5	-	-	-	-	-	-	5-5
CO_3	-	-	-	30-215	-	-	-	-	-	-	30-215
Cr	-	-	-	-	-	0.002-0.004	0.020-0.13	T[b]-1.8	-	-	0.002-1.8
F	-	-	-	1.2-4.2	-	-	-	-	-	-	1.2-4.2
Fe	-	-	-	-	0.0004-0.0005	0.0005-0.0006	0.003-0.042	0.004-0.04	-	-	0.0004-0.042
HCO_3	-	-	-	22-40	-	-	-	-	-	-	22-40
K	-	-	-	6-7.5	0.76-0.84	1.2-2.9	2.1-3.4	5.2-16	0.1-0.25	0.07-1.2	0.07-16
Li	-	-	-	-	0.020-0.10	0.33-0.91	0.092-0.18	0.099-0.42			0.020-0.42
Mg	-	-	-	0.26-4.0	0.072-0.86	0.034-0.040	0.013-0.0	0.002-0.009		0.008-0.02	0.002-0.0
Mo	-	-	-	-	T[b]	T[b]	T[b]	T[b]			T[b]
Na	-	-	-	12-235	12-21	8.8-43	22-95	11-77	0.2-0.55	0.05-0.21	0.05-235
NO_3	-	-	-	0.2-2.6	-	-	-	-	-	-	0.2-2.6
OH	-	-	-	22-40	-	-	-	-	-	-	22-40
Pb	-	-	-	-	-	0.014-0.017	-	-	-	-	0.014-0.017
Si	-	-	-	25-68	-	-	-	-			25-68
SO_4	-	-	-	50-130	-	-	-	-	0.8-2.8	0.26-0.60	0.26-130
Sr	-	-	-	-	0.004-0.01	0.50-2.8	1.4-2.4	1.8-8.7	-	-	0.004-8.7
Zn	-	-	-	-	0.001-0.011	0.008-0.026	0.011-0.020	0.008-0.021	-	-	0.001-0.025
TDS	0-440[c]	250-6700[c]	520-2800[c]	251-782	90-108	610-1120	406-558	618-944	-	-	0-2800
TOC	1.8-6.8[c]	1.0-4.4[c]	2.9-11.8[c]	34-98	-	-	-	-	-	-	1.0-38
Organic N	0.07-0.14	0.07-0.09	0.09-0.13	-	-	-	-	-	-	-	0.09-0.14
Phenols	0.03-0.04	0.02-0.03	0.015-0.022	-	-	-	-	-	-	-	0.02-0.04
pH	7-10	11-12	11-12	10.4-11.2	8.59-10.6	11.6-12.0	7.76-12.0	12.0-12.7	-	-	7.76-12.7

[a] B = batch; C = continuous flow.
[b] T indicates a trace detected.
[c] Upper limit derived with 80-hour continuous flow columns.
[d] Water-to-shale ratio varied from 7 to 75 ml/g.

Ca is higher in high-temperature inert leachates and K is higher in high-temperature combustion leachates.

The levels of Mg are higher in leachates derived from low-temperature runs.

Kuo et al (29) conducted batch and continuous-flow leaching studies of simulated and field in situ spent shales from the Occidental modified in situ process. In Kuo's work, a series of samples from Occidental Research's "mini-retort" that covered temperatures from 540 to 900°C, shale grades from 10 to 37 gallons per ton, and particle sizes from 0.3 to 4 cm, were leached with de-ionized water at room temperature. Additionally, a core from Retort 3E at Logan Wash, Colorado, was leached in a Soxhlet apparatus. The principal conclusions of these investigators were as follows:

The major ions in the leachates were Ca, Na, K, OH^-, and $SO_4^=$.

Ca, Na, and K concentrations reached maxima between 750°C and 850°C.

Spent shales from undiluted air runs were more leachable at all temperatures than spent shales from air-steam runs.

The concentration of most ions except OH^- and Ca reached negligible levels in leachate in the first five pore volumes of water for shales retorted at temperatures greater than 650°C.

If one considers only the maximum observed value for each constituent in Table 12, the constituents may be grouped according to how much is leached. This grouping is as follows:

Less than 10 mg/100 g: Al, B, Cl^-, Cr, F^-, Fe, Li, Mo, Mg, NO_3^-, Pb, Sr, Zn

Between 10 and 100 mg/100 g: HCO_3^-, K, $OH^=$, Si

Greater than 100 mg/100 g: Ca, $CO_3^=$, Na, $SO_4^=$

This grouping shows that the major inorganic constituents in the leachate are K, Ca, Na, $SO_4^=$, Si, OH^-, HCO_3^-, and $CO_3^=$.

Study of raw shale and spent shale from Occidental Oil Shale, Inc's. Logan Wash site (32) show no tendency for trace metals such as As and Mo to preferentially report to the leachate. Data from leaching studies show a greater tendency to leach As and Mo from the raw shale than from the spent shale. Partitioning studies on oil shales (33) show that such species as Hg and As tend to appear in the retort off gases reducing the potential for leaching from the spent shales.

4.2.1.2 Assessment of Impact Potential

Given the variations in the types of data and the wide variations in amounts of materials leached, it is difficult to assess the potential impacts of in situ oil shale technology on groundwater. It is clear that potentially large amounts of organic and inorganic materials may be leached from the spent shale remaining in the retort after operations. In some areas where such operations might be conducted, e.g., certain resources in Utah and Wyoming, the potential for any groundwater intrusion is small because the sites are dry. In the major resource area of the Piceance Creek Basin of Colorado, however, this is not true. Based on the data summary in Table 12 (last column), Fox (34) has estimated the average maximum compositions of leach waters exiting lease tracts C-a and C-b. The results are given in Table 13. The work of Weeks et al (35) indicates that flow will be

down on Tract C-a and up on Tract C-b. Therefore, retorts on C-a will be leached with upper aquifer water and on C-b with lower aquifer water.

This estimate indicates that the average concentration in the leachate for tabulated constituents may greatly exceed levels in native groundwaters. On Tract C-a, flow is projected to be downward, and leachate with a composition similar to column (6) of Table 13 will mix with and be transported in the lower aquifer, which has an average quality as indicated by column (3). A comparison of lower values in column (6) with column (3) indicates that Al, Cl^-, $CO_3^=$, Fe, Li, $NO_3^=$, Si, $SO_4^=$, and phenols will increase, that TDS, B, F^-, HCO_3^-, and Na decrease; and that K, Pb, Zn, and TOC remain about the same in lower aquifer waters. Major increases in all of the tabulated parameters will occur if the upper values in column (6) are considered.

On Tract C-b, flow is projected to be upward, and leachate with a composition similar to column (7) will mix with and be transported in the upper aquifer which has an average quality as indicated by column (4). A comparison of the lower values in column (7) with column (4) indicates that Al, B, Cl^-, Cr, $CO_3^=$, F^-, Fe, $HCO_3^=$, K, Li, Na, $NO_3^=$, Pb, Si, TDS, and TOC will increase in the upper aquifer while $SO_4^=$ will decrease and Zn will remain about the same. Major increases in all of the tabulated parameters will occur if the upper values in column (7) are considered.

From these data, Fox concludes that the quality of post-development groundwaters may still be suitable for certain irrigation applications but not for either domestic supplies or livestock watering without extensive treatment to remove trace inorganics, such as Pb, Fe, F^-, and Cr and organics such as phenols. Based on the low groundwater flow rates on the two tracts, it may take many years for leachate to travel distances of a few miles from the abandoned retorts. Therefore, treatment of the groundwater will most likely be required. Current technology limits this approach to

TABLE 13. ESTIMATED COMPOSITION OF LEACHATE EXITING AN IN SITU RETORT LOCATED ON LEASE TRACTS C-a AND C-b

Constituent	Distilled Water Leachate Composition mg/100g (1)	Predevelopment Groundwater Quality, mg/l				Leachate Composition, mg/l	
		Tract C-a		Tract C-b			
		Upper Aquifer (2)	Lower Aquifer (3)	Upper Aquifer (4)	Lower Aquifer (5)	Tract C-a[a] (6)	Tract C-b[b] (7)
Al	0.095-2.8	0.14	0.24	0.3	0.3	0.49-31	0.89-53
B	0.001-014	0.33	0.84	1.4	36	0.33-1.9	36-39
Ca	0.03-210	35	8.8	32	14	35-2350[c]	14-3950[c]
Cl	5.5	12	22	26	1200	32-73	1234-1300
CO_3	30-215	0.88	69	21	220	110-2400	408-4250
Cr	0.002-1.8	<0.01	<0.01	0.002-0.3	<0.009	<0.02-<20	0.01-34
F	1.2-4.2	0.41	15	10	21	4.8-47	29-100
Fe	0.0004-0.042	5.0	0.78	0.5	0.8	5.0-5.5	0.8-1.6
HCO_3	22-40	482	842	790	4000	560-920	4140-4750
K	0.07-18	2.2	2.6	2.2	21	2.5-200	21-360
Li	0.020-0.42	0.13	0.13	<3.1	10	0.20-4.8	10-18
Mg	0.002-8.0	52	20	42	11	52-140[c]	11-160[c]
Na	0.05-235	212	397	330	2500	212-2800	2500-6900
NO_3	0.2-2.6	0.21	0.1	0.41	0.46	0.94-30	1.7-49
Pb	0.014-0.017	0.17	0.21	0.01	0.03	0.22-0.36	0.12-0.35
Si	25-88	26	10	17	13	120-990	170-1660
SO_4	0.28-130	325	112	220	63	326-1800[c]	65-2500[c]
Zn	0.001-0.025	0.26	0.24	0.2	0.2	0.26-0.54	0.2-0.7
TDS	0-2800	905	1075	1100	6190	905-31,700	6190-58,700
TOC	1.0-38	8.5	11	3	10	12-430	16-720
Phenols	0.02-0.04	0.003	0.002	-	-	0.04-0.44	0.06-0.8

[a]Assumes the retort is leached with upper aquifer water, that the mass of spent shale in the retort is 1.1×10^9 g, and that the volume of water contained by the retort is 5.0×10^8 liters. Computed using Eq. (7). For example, the lower value for TOC shown in column (6) is given by:

$$\frac{(10)(1.0)(1.1 \times 10^9) + (8.5)(5.0 \times 10^8)(6)}{(6)(5.0 \times 10^8)} = 12 \text{ mg/l}$$

[b]Assumes the retort is leached with lower aquifer water, that the mass of spent shale in the retort is 7.5×10^8 kg, and that the volume of water contained by the retort is 2.0×10^8 liters. Computed using Eq. (7). For example, the lower value for TOC shown in column (7) is given by:

$$\frac{(10)(1.0)(7.5 \times 10^8) + (10)(2.0 \times 10^8)(6)}{(6)(2.0 \times 10^8)} = 16 \text{ mg/l}$$

[c]These constituents may be reduced on passage through the groundwater aquifer.

Source: (14)

pumping and treatment at the surface prior to reinjection. Such a requirement could involve a multi-year effort in order to ensure leaching of all spent shale in the retort with groundwater.

4.2.2 Subsidence

The degree of subsidence which might occur as a result of in situ oil shale retorting is dependent upon the void volume created by resource extraction. Compared to UCG where the coal has an ash content of less than 30 percent by weight, oil shale has an ash content of 90 percent or more, depending upon the grade of shale. This factor is important when assessing the potential impacts. The considerations regarding depth, cavity size, resource thickness, and overburden characteristics mentioned in Section 3.2.2 for UCG also apply to in situ oil shale retorting.

4.2.2.1 Impacts Observed to Date

No surface subsidence has been observed during any of the field tests to date. This is not surprising given the low mass removal from the resource even if 100 percent of the shale oil could be recovered.

4.2.2.2 Assessment of Impact Potential

The potential for subsidence is low for this technology for true in situ retorting operations. This is due to the generally high competence of the overburden strata and the low mass removal. In addition, oil shale swells upon heating and expands up to 15 percent. This additional bulking is sufficient to provide support for any void that might be created.

Similar considerations also apply to vertical modified in situ retorting. However, the potential for subsidence is somewhat greater due to the removal of 20 to 40 percent of the oil shale prior to retorting. Any effects of explosively rubblizing the column of oil shale on the strength of

the remaining overburden may increase the chances for subsidence if any weakening results. A proposed commercial operation at Tract C-b in Colorado includes operation of 96 retorts simultaneously. Each retort is 165-feet x 165-feet x 290-feet high (36). This is essentially the same scale as Retorts 6, 7, and 8 operated at Logan Wash, Colorado, by Occidental Oil Shale, Inc. This experience to date should keep the potential for subsidence low for future commercial operations.

4.2.3 Post-Operational Gas Leakage

The conditions under which in situ oil shale retorts are operated is significantly different in one essential parameter from UCG. The retort pressure is generally low, i.e., inches of water to 1-2 psig and even less than atmospheric if induced draft blowers are used at the product off take points to remove gases from the retort. The gas composition for a proposed commercial facility is given in Table 14 (36).

4.2.3.1 Observations to Date

No post-operational gas leakage to atmosphere has been observed to date. However, monitoring during early operations at Geokinetics' site south of Vernal, Utah, indicated losses to atmosphere (37). Fugitive hydrocarbon emissions rates from 0.001 to 0.009 pounds per square foot of surface area per day were measured during operation of Retort 17. This problem is unique to the Geokinetics project due to the shallow depth (< 100 feet) of the shale resource at this site. Retort 17 involved operations in a 17-foot thick bed with only 26 feet of overburden. Explosive fracturing of the oil shale with resultant lifting of the ground surface to create void volume in the retort resulted in creation of leakage pathways to the atmosphere for the hydrocarbons detected during monitoring. Additional experience gained from operation of a number of retorts at greater depths since No. 17 has produced improved fracturing with elimination of these gas losses to atmosphere.

TABLE 14. COMPOSITION OF MIS RETORT GAS

Component	MWt	Wet Basis	
		Mass %	Mole %
H_2	2	0.50	6.50
CO	28	1.30	1.21
CO_2	44	29.26	17.28
N_2	28	45.21	41.96
NH_3	17	0.26	0.40
H_2S	34	0.16	0.12
CH_4	16	0.69	1.11
C_2H_4	28	0.09	0.08
C_2H_6	30	0.20	0.18
C_3H_6	42	0.09	0.06
C_3H_8	44	0.14	0.08
C_4	72.35	0.22	0.08
Light Oils	110.71	0.52	0.12
COS	60	0.01	0.003
CS_2	76	0.002	0.001
CH_3SH	48	0.003	0.001
H_2O	18	21.34	30.81
TOTAL		100.00	100.00

Source: (36)

4.2.3.2 Assessment of Potential Impacts

So long as subsidence to the surface or, in the case of the Geokinetics, Inc. process, excessive fracturing of the overburden do not occur the potential for operational as well as post-operational leakage should be of low probability. If either condition does occur, potentially large volumes of gas containing significant quantities of H_2, CO, CH_4, NH_3, H_2S, and hydrocarbons as shown in Table 14 could be released to atmosphere. For the commercial operation described for Tract C-b (36), each retort contains about two million scf of gas. The retort size for commercial operation of the Geokinetics process is significantly smaller with each retort containing about 250,000 scf of gas of similar composition to that in Table 14.

4.2.4 Co-produced Solid Wastes

As with UCG, entrained dust is carried to the surface in the off gases from in situ oil shale retorts. This material is most likely small particles (< 5μ) due to the low pressure and low gas velocities in the retorts consisting of shale dust. The material recovered from the gas stream will be coated with shale oil since the first point of recovery will most likely be in the gas demisters where entrained shale oil mists are condensed from the gas prior to combustion of these off gases for steam generation. The disposal of this particulate matter may be regulated under the Resource Conservation and Recovery Act.

4.2.4.1 Observations to Date

Particulate matter production rates (37) for Retort 17 at the Geokinetics site show production of 0.9 pounds/hour of material after removal of hydrocarbons coating the particulate matter. This rate of production was determined by monitoring the incinerator exhaust gases. Measurements at the demister outlet prior to incineration showed a particulate production rate of

2.4 pounds/hour. The difference is presumably condensed hydrocarbons. Retort 17 produced shale oil at a rate of 30 barrels/day.

4.2.4.2 Assessment of Potential Impacts

Assuming the particulate production rates determined at the Geokinetics site are representative of in situ oil shale retorting operations, production of 2,000 barrels/day of shale oil—the scale of operations proposed by Geokinetics—would yield 700 tons/year of oily particulate matter. If all of the condensed hydrocarbons were washed from the material, the amount would decrease to about 300 tons/year. This amount of material would most likely be disposed of off-site rather than constructing a special disposal area on-site. For the commercial C-b tract facility (36), 69,000 barrels/day are produced from the modified in situ retort. At this rate of production, about 24,000 tons/year of oily particulate matter are produced. Washing to remove condensed hydrocarbons decreases this amount to 9,000 tons/year. If the particulate loading is similar to that assumed for commercial UCG operations (0.1 gr/scf), the particulate matter production rate for the 69,000 barrels/day C-b plant is about 10,000 tons/year of oily particulate matter. This range of production rates would most likely require on-site disposal in a specially designed landfill.

SECTION 5

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